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# 1. PRESENTATION OF THE DATABASE

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## INTRODUCTION

With the continuous progress in hardware and numerical schemes, Computational Unsteady Aerodynamics (CUA), that is, the application of Computational Fluid Dynamics (CFD) to unsteady flowfields, is slowly finding its way as a useful and reliable tool (turbulence and transition modeling permitting) in the aircraft, helicopter, and missile design and development process. Before a specific code may be used with confidence it is essential to validate its capability to describe the physics of the flow correctly, or at least to the level of approximation required, for which purpose a comparison with accurate experimental data is needed. Unsteady wind tunnel testing is difficult and expensive; two factors which limit the number of organizations with the capability and/or resources to perform it. Thus, unsteady experimental data is scarce, often restricted and scattered in diverse documents. Additionally, access to the reports does not necessarily assure access to the data itself. The present publication was conceived with the aim of collecting into a single easily accessible document as much of the good quality data as possible.

The idea is not new. In 1982 AGARD's Structures and Material Panel (SMP) produced the AGARD Report No. 702 'Compendium of Unsteady Aerodynamic Measurements', which has found and continues to find extensive use within the CUA community. Report 702 is primarily focused on aeroelasticity, with particular attention paid to transonic conventional flutter. In 1995 AGARD's Fluid Dynamics Panel (FDP) decided to update and expand the former database with new geometries and physical phenomena and launched Working Group WG-22 on 'Validation Data for Computational Unsteady Aerodynamic Codes'. Shortly afterwards AGARD was reorganized as the RTO (Research and Technology Organization) and the WG was renamed as AVT (Applied Vehicle Technology) WG-003. The group, chaired by the author of this introductory chapter, first met in spring 1997 and closed its effort 5 meetings later in spring 1999 with the present publication. Special care was taken that both theoreticians and experimentalists were represented in the Working Group. Table 1 gives the complete list of WG members including address, telephone, fax and e-mail. Other contributors who were not formal members of the group are identified as authors of individual chapters.

## REQUIREMENTS FOR EXPERIMENTS

The type of experiment included in this publication falls under the general category of validation experiments, that is, those made on geometrically simple "generic shapes" designed to provide sufficiently detailed measured data for the verification of the physical representation provided by the CFD code. This requires that the data be taken and presented in a form and level of detail consistent with CFD requirements and that the accuracy of the experimental data be thoroughly documented and understood. The ideal test case should provide:

a) Accurately measured model shape and surface finish.
b) The actual position and motion of all points of the model, including both static and dynamic elastic deformations.
c) Well defined state of the boundary layer on the model.
d) Inflow and outflow conditions.
e) Wall conditions and wall boundary layer.
f) Specification of support interference
g) Specification of the accuracy of measured data.

After a thorough screening of the candidate test cases available for general distribution, it was found that ideal test cases are rare indeed, so the acceptance criteria had to be dramatically modified to the minimum requirements of knowing the geometry, and the motion (rigid and elastic) as accurately as possible. Nevertheless the WG believe the test cases included in this report to be generally of very high quality.

It has been the aim to select cases with very detailed information (e.g. a lot of pressure points), but cases with less detailed information, but a wide range of flow conditions, have also been acceptable. Wherever possible experiments have been selected which include different levels of physical difficulty so that the CFD researcher can use a staircase approach to the problem of validating the code.

Generally, agreement on the steady pressure distribution is a prerequisite for agreement on the unsteady pressures, when comparing calculations with experimental data. In particular, when shock waves are present the experimental and theoretical distributions of unsteady pressure will not agree unless there is already agreement with the mean position and strength of the shock. For this reason a fair amount of steady data has also been included.

## COMPUTATIONAL RESULTS

In addition to the experimental data, this publication includes computational results. Before a code can be validated, the developer must first verify that it solves accurately the mathematical model that it uses of the real world. Given the lack of analytical solutions to the 3-D versions of the various sets of equations of interest to CUA, verification is best achieved by means of comparison with another computational solution of the same set of equations.

To this aim a benchmark exercise was performed on the F-5 wing. Computational results covering the whole spectrum from Unsteady Transonic Small Perturbations to Navier-Stokes codes were generated and are provided in the database, thus facilitating the verification of the new code against the same level of physical modeling.

For the same reason, attempts have been made to complement each experimental data set with an example of a numerical calculation of at least one of its test points. These results may also be useful in cases where the CFD developer finds intriguing differences with experimental data, which cannot be attributed in a straightforward way to deficiencies in the numerical model, or in the test. Comparison with another computational result may clarify whether code improvement is required. Unfortunately it has not been possible to obtain numerical results for most of the test cases, but the door is left open for interested groups to submit their calculations to complete the picture. These 'late arrivals' could be compiled as an addendum to this document.

No claim is made that any of the CFD solutions included are free of discretization or solution errors. They should be treated as examples of what people with experience in the field have produced using mature codes, but not as absolute truth.

## ORGANIZATION OF THE DATA BASE

The compendium consists of this general introduction, a chapter on analytical solutions, a review of AGARD-R-702, the F-5 benchmark exercise mentioned above, and 19 self-contained datasets, which are summarized in Table 2. For each test case the following information is provided:

- A brief overview of the purpose and salient features of the experiment
- Nomenclature information (no attempt has been made to assure uniformity of notation across the data sets).
- A standard form (taken directly from Report 702 as this was considered difficult to improve, with appropriate adaptations for some of the cases) with the key information about the test conditions and equipment that a user may require.
- Information on the layout of the data files when it was not self-explanatory
- Figures and pictures to illustrate the case

When available, the associated computational results are presented in a chapter immediately following the experimental counterpart.

The data itself is only provided in machine-readable form in the CD-ROM that accompanies this publication. Each case is included in a different folder, where the various relevant data files are stored. Most of the data files are plain ASCII, with some being written in TECPLOT format. In some cases it was necessary to provide geometry information by means of CATIA files. Figures are included in a number of well-known formats (eps, pdf, etc). A copy of the different chapters is also provided in Word 97 format.

## OVERVIEW OF THE CASES

Immediately following this general review the reader will find a chapter on analytical solutions of the 1-D unsteady Euler equations as well as other simplified equations (Linear Advection, Burger's, etc.). Comparison with analytical solutions is a necessary (albeit often neglected) first step in the process of code verification. The classical problems described in the chapter:

- Shock Tube (Riemann) problem
- Propagation and reflection of a moving shock at the closed end of a tube
- Expansion and compression flows behind moving pistons

provide excellent opportunities to check respectively: the time-accuracy of shock convection (particularly for implicit methods); the numerical implementation of unsteady boundary conditions; and moving grids.

Next in line the reader will find a chapter devoted to the AGARD-R-702. The original Compendium has been revisited with the perspective of time, and those cases, which have found more use, are included here again. Nothing has been added to them, but the data is provided in electronic format, which will make the user's life easier. The reader will probably miss the well-known LANN wing. Different problems encountered in the preparation of the electronic data have prevented the group to incorporate this case, which would otherwise have been included as it has found extensive use in spite of (or perhaps because of) the difficulties introduced by its elastic deformation.

The already mentioned F-5 wing benchmark exercise follows next. Computational results covering the whole spectrum from Unsteady Transonic Small Perturbations (UTSP) to time-accurate Navier-Stokes codes, with different levels of grid refinement and/or geometrical simplifications (tip, trailing edge, etc) are included. While the steady solutions compared quite well, with differences being easily attributable to grid or viscous effects, the unsteady solutions show surprisingly large discrepancies. A detailed analysis can be found in Chapter 4.

The test cases themselves follow in the remaining chapters; they have been loosely classified under 6 categories:

- Flutter
- Buffet
- Stability & Control
- Dynamic Stall
- Cavity Flows
- Store Separation

Not surprisingly, the database is well populated with an assortment of flutter-type cases. The category seems to be well balanced, covering from very simple to more complicate geometries and from linear to highly non-linear flows. Some of the cases have been available for a long time (although it is the group's opinion that good data never ages) but they were considered to be still useful and relevant.

The database starts with the well-known F-5 wing tested in the High Speed Wind Tunnel of NLR. The original purpose of the experiment was to determine the unsteady airloads characteristics on a representative fighter type wing oscillating in pitch. It constitutes a very comprehensive data set, which progressively builds up in geometric complexity from the clean wing to a wing with a tip launcher and an A-A missile with canards and fins. From a computational point of view, the clean wing case can be considered as rather benign, as it involves only small static angles of attack, small amplitudes of oscillation and limited viscous effects. This fact together with its simple geometry and wide range of Mach numbers tested (from subcritical to low supersonic) make it an ideal 'first case' in the validation process of a new code. This was the main reason why it was selected for the benchmark exercise mentioned before. On the other hand, the wing plus launcher plus missile cases provide excellent opportunities to check the ability of the code to tackle rather complex geometries.

Test case 6E is the Rectangular Supercritical Wing model. The RSW was tested in the NASA Langley Transonic Dynamic Tunnel (TDT) with the specific aim of obtaining data for CFD comparison. It has a simple low aspect ratio unswept rectangular planform with no twist, a constant 12% thick supercritical airfoil and a tip of revolution. The model undergoes pitching oscillations. Data is provided corresponding to a wide range of flow conditions from low subsonic to strong transonic well beyond the design Mach number, as would be required for flutter verification beyond cruise conditions. A broad range of reduced frequencies is also covered. Special care has been taken to select data points, which illustrate the trends with Mach number, reduced frequency, amplitude of oscillation and static angle of attack. Some cases for high angle of attack (at low speed) and others for the effect of transition have been also included. Despite its simple geometry, the case has proved to be a difficult one to calculate. Typically for low-aspect ratio rectangular wings, transonic shock waves tend to sweep forward from root to tip such that there are strong three-dimensional effects. Additionally it has been found to be very sensitive to viscous and transition effects, specially on the undersurface.

Test cases 7E and 8E were part of NASA's Benchmark Model Program (BMP) which tested in Langley's TDT a number of models with the same rectangular planform but with different airfoils with diverse transonic characteristics. The first model had a NACA 0012 airfoil which develops strong shocks ahead of mid-chord; the second model had a NACA 64A010 airfoil with a milder evolution of the shock which initially forms at mid-chord; and the third model had a supercritical SC(2)-0414 airfoil with strong aft loading and the associated low upper surface curvature which generates weaker hard to capture shocks. In addition the Benchmark Active Control Technology (BACT) model had also a NACA 0012 airfoil but with a trailing edge control surface, and a pair of independently actuated upper and lower surface spoilers for use in flutter suppression and dynamic response excitations. All the models were mounted on the PAPA (Pitch and Plunge Apparatus) 2 Degrees of Freedom dynamic system, which allows rigid models to undergo flutter. Cases corresponding to classical pitch-plunge flutter, transonic stall flutter involving shock waves and separating and re-attaching flows during the cycle of motion, and a shock-induced plunge instability are included. The actual wing motion together with the corresponding pressures are provided, thus allowing a staircase approach to validation, from forced oscillations (using the measured pitch-plunge motion as input) to 'simple' aeroelastic simulations (using the known elastic characteristics of PAPA). Finally the transfer functions of control surface inputs measured with the BACT can be used to validate aeroservoelastic codes. These two cases together provide an extremely comprehensive dataset, which is sure to keep CFD developers busy for a long time.

The Clipped Delta Wing model of test case 9E was also tested in the NASA Langley TDT. The planform was derived by simplifying that of a Supersonic Civil Transport aircraft, resulting in a trapezoid wing with an unswept trailing edge and without twist and camber. The model undergoes pitching and trailing edge control surface oscillations. A rather thick (for a supersonic transport) 6% symmetrical circular arc section was used, which very much enhances transonic effects. Additionally the highly swept sharp leading edge separates the flow at relatively low angles of attack forming a leading edge vortex, which sometimes co-exists with a shock wave, making this a challenging case for any numerical method.

Case 10E was tested in ONERA S2 wind tunnel to obtain a database of the unsteady behavior of control surfaces in high supersonic conditions. It consists of a 5.5 aspect ratio rectangular wing with a 7% symmetric bi-convex airfoil and an oscillating trailing edge flap. Detailed pressure information was measured at the mid semi-span section, which at the supersonic Mach numbers tested is effectively in 2D conditions. Test points are provided that illustrate the effect on the unsteady airloads of: Mach number, steady angle of attack, mean flap deflection, flap oscillation amplitude and oscillation frequency.

The RAE Tailplane constituting case 11E was tested in RAE's 3 ft tunnel to provide data for the validation of codes for the prediction of unsteady pressures on low aspect ratio configurations suitable for wings or controls of military aircraft. The model has again a thick (for supersonic applications) NACA 64A010 airfoil, which was oscillated in pitch at a wide range of frequencies and Mach numbers. It constitutes an excellent challenge for any 3D supersonic code, with the added bonus that the model was build in carbon fiber, which provided both high stiffness and low inertia, thus minimizing aeroelastic distortions.

The opposite (in terms of aeroelastic deformations) is true for test case 12E. This model of a Supersonic Transport with a double-swept-back arrow wing, a fuselage and an oscillating trailing edge flap was tested at NAL's 2mx2m transonic wind tunnel with the specific purpose to accumulate validation data for CUA and ACT (Active Control Technology) codes. A NACA0003 airfoil was used, resulting in a very thin wing with non-negligible static and dynamic elastic deformations. These deformations were very carefully monitored tracing optical targets installed on the wing surface. Furthermore, in some cases the trailing edge was made to oscillate at frequencies close to the eigenfrequencies of the model. Although the flow characteristics are not very demanding (no strong shock waves appear) the elastic motion further complicates its accurate prediction. It thus constitutes an excellent test of the ability of the code to handle elastic problems. Results are included for different transonic Mach numbers, mean flap positions and frequencies of oscillation.

The buffet category starts with test case 13E corresponding to the shock-induced buffet of the BGK No 1 supercritical airfoil tested at IAR's 2D High Reynolds Wind Tunnel. This dataset provides very rich pressure information on a number of points outside, at, and well inside, the buffet onset boundary. Additionally skin friction data is available allowing the user to monitor the merging of the shock induced separation bubble with the trailing edge separation.

Test case 14E extends the buffet information to wing configurations with Model 2391 tested in DERA Bedford 13ftx9ft low speed wind tunnel. This is a low mass, high stiffness model designed to obtain data of the aerodynamic excitation arising from unsteady separated flow without the interferences due to model vibration and/or support natural frequencies. It is a 40° sweep diamond wing with a streamwise clipped tip. Two interchangeable fuselages were tested, respectively rectangular and chined, with the former providing a perpendicular wing-fuselage interface, and the later allowing the study of buffet due to mixed vortical flow. Very rich pressure information for angles of attack up to 30° is included, thus providing an excellent test case to validate the buffet part of any buffeting prediction code.

Finally, test case 15E1 closes the buffet category with the Standard Dynamic Model (SDM) tested in IAR's Low Speed Wind Tunnel to investigate the aerodynamic excitation during wing and/or fin buffet of a generic fighter aircraft configuration. It was also build extremely stiff so as to avoid any buffeting. Wing and fin buffet cases corresponding to bursting of strakes and/or forebody vortices (both symmetric and asymmetric) are presented. The rather complicated geometry together with the very difficult physics pose a real challenge for any CFD code.

The Stability & Control category is mainly devoted to high-angle of attack oscillations. Test cases 16E and 17E present similar 65° delta wings and explore their aerodynamic behavior during high performance maneuvers involving large amplitude, high-rate, pitching/rolling/yawing motions at high incidence. The first case, presented by IAR, was tested in two different wind tunnels using two different support systems with very similar results; so it can be assumed to be fairly free of support and wall interferences. It mainly presents global coefficients with limited pressure information. The second case, tested at DLR, has more extensive pressure data. It presents a range from simple attached flow, through fully developed vortex flow and vortex bursting upstream and downstream of the trailing edge, up to deadwater type flow on the upper surface; thus allowing a code validation with progressively more complex physics.

Test cases 18E and 19E can again be treated together. They correspond to straked delta wings tested at respectively subsonic and transonic speed in NLR's LST and HST wind tunnels, with the aim to improve understanding of unsteady loading on fighter like wings during pitch oscillations and maneuvers. They present a wide range of flow topologies, from attached to vortex breakdown over the whole model. Additionally the transonic test includes cases with shock induced trailing edge separation, leading edge separation and vortex breakdown at transonic speeds, and Limit Cycle Oscillations (LCO). The data points selected cover all the different flow types, including the influence of Mach number, static incidence and sideslip, amplitude and frequency of oscillation, thus proposing test points ranging from relatively easy to extremely difficult to calculate.

The cavity category is represented by 2 datasets (test cases 20E and 21E) produced respectively by BAe/DERA and DLR. In both cases very rich pressure information inside rectangular cavities at different Mach numbers is provided. Acoustics as well as loads and store separation specialist will benefit greatly from these test cases.

A whole set of dynamic stall test cases is included in chapter 22E. Both 2D and 3D configurations undergoing "ramp-up", "ramp-down" (to isolate the stalling mechanism from the re-attachment process) and harmonic pitching oscillations are considered. Detailed pressure and loads information for different pitch rates and mean angles of attack are included, thus providing the CFD developer with a variety of test data to assess the output of their codes, with many of the cases constituting a severe tests of the ability of the code to capture massively separated flows.

Finally a store separation case (test case 23E) is included The test was performed at AEDC by means of a CTS (Captive Trajectory Support) so that strictly speaking data is only quasi-steady. Nevertheless the case has been included because the modeled phenomena is unsteady by nature, and this type of data is comparatively difficult to find in the open literature. Additionally the store's boundary layer transition is very far aft and has a strong influence on global coefficients, which increases the challenge for NS solvers.

It is recognize that the database lacks an isolated missile type configuration. This is unfortunate, as missile aerodynamics is an area where unsteady effects are playing an increasingly important role with the permanent increases in maneuverability. It is hoped that such a case be offered in the near future.

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## Table 2. Test cases

| ID | Test case | Configuration | Motion | Speed Regime | CFD? |
|---|---|---|---|---|---|
| 5E | NLR F-5 Wing & Wing+Store | Wing+Missile | Pitch | Subsonic to Supersonic | YES |
| 6E | NASA RSW | Wing | Pitch | Subsonic to Transonic | |
| 7E | NASA BMP Rectangular Wing | Wing | Pitch Plunge | Subsonic to Transonic | |
| 8E | NASA BMP BACT | Wing + Flap + Spoiler | Flap spoiler | Subsonic to Transonic | YES |
| 9E | NASA Clipped Delta Wing | Wing + Flap | Pitch Flap | Subsonic to Supersonic | |
| 10E | ONERA 2D Supersonic TE Control | Airfoil + Flap | Flap | Supersonic | |
| 11E | RAE Tailplane | Wing | Pitch | Supersonic | |
| 12E | NAL SST | Wing + Flap + Fuselage | Flap | Transonic | |
| 13E | IAR BGK Airfoil | Airfoil | Buffet | Transonic | |
| 14E | DERA Model 2391 | Wing + Fuselage | Buffet | Subsonic | |
| 15E | IAR SDM Fin Buffet | Wing + Fuselage + Fin | Buffet | Subsonic | |
| 16E | IAR 65° Delta Wing | Wing + Centerbody | Roll | Subsonic | YES |
| 17E | DLR 65° Delta Wing | Wing + Centerbody | Pitch Yaw Roll | Subsonic | YES |
| 18E | NLR Low Speed Straked Delta Wing | Wing | Pitch | Subsonic | |
| 19E | NLR Transonic Simple Straked Delta Wing | Wing | Pitch | Subsonic to Transonic | |
| 20E | BAe/DERA Cavity | Cavity | - | Subsonic to Supersonic | |
| 21E | DLR COM TWG1 | Cavity | - | Transonic Supersonic | |
| 22E | Glasgow U. Dynamic Stall | Airfoil Wing | Pitch | Subsonic | |
| 23E | AEDC Wing/Pylon/Moving Store | Wing + Pylon + Store | Drop | Transonic Supersonic | |